Nicols, L.H.

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ON SEPARATING THE EFFECTS OF RADIATION AND CONVECTION IN THE PROCESS OF AIR COOLING

by

L. H. Nichols, B. A.

Experiments carried out under the direction of

Dr. A. N. Shaw

at

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McGill University, and at the University of Alberta

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"ON SEPARATING THE EFFECTS OF RADIATION AND CONVECTION IN THE PROCESS OF AIR COOLING"

ct. I

INTRODUCTION

In certain problems of heating and ventilation it is important to determine what portion of the heat imparted to a given enclosure leaves the source of heat by convection and what by radiation. The ratio of these two has a fundamental bearing on the economy of the heating system and upon the healthiness of a room. If heat is conveyed to a person mainly by convection of air, which is much warmer than the surrounding objects, the conditions are less healthy than where a larger proportion is received by radiation through cooler air. On the other hand, if heat is conveyed almost entirely by direct radiation, it will be found that the extreme is again unsatisfactory and usually associated with great economic inefficiency in the system of heating. The study of these conditions is still in an incomplete stage mainly because it is frequently difficult to determine in a definite case what relative parts radiation and convection are actually playing. In designing heating systems, it has been much easier to resort to "trial and error" methods leading slowly to apparent increases in comfort and economy, than to determine in advance the optimum conditions demanded and then design accordingly.

The influence of incident radiation and turbulent air upon the cooling of hot parts of machinery, upon the cooling of hot

wires, upon the drying of materials and in many other industrial processes, is clearly of great importance, and a knowledge of the relative influence of these factors has been desirable but difficult to obtain. In the use of thermometers, hygrometers and other instruments, it is well known that exposure to incident radiation renders their readings unreliable, and the means of correcting these readings for exposed use has never been satisfactorily developed.

DESCRIPTION AND THEORY

A problem of this type arose while a series of tests was being carried on in the open air with several standard anemometers and a "kata"-thermometer[1] used as an anemometer.[2] The "kata"-thermometer, in brief, consists in an alcohol thermometer with a relatively large bulb of definite surface area and stem of about 1 mm. bore, on which 95° and 100° F. are marked. (see Fig. I) The bulb is held in hot water until the alcohol, coloured red for visibility, has partly filled a small reservoir

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1. Hill, Griffith and Flack, "The measurement of the rate of heat loss at body temperatures by convection, radiation and evaporation." Phil. trans. Roy. Soc. London, B. Vol. 307, p 201 (1915) Also Hill, F. and Hargood Ash, "On the Cooling and Evaporative Powers of the Atmosphere as Determined by the Kata-thermometer". Proc. Roy. Soc. B., Vol 90. pp.438-447 (1919)
2. A. Norman Shaw, "Notes on the Comparison of Anemometers Under Open-air Conditions". Monthly Weather Review, Jan. 1919, 47: 25-26

KATA THERMOMETER

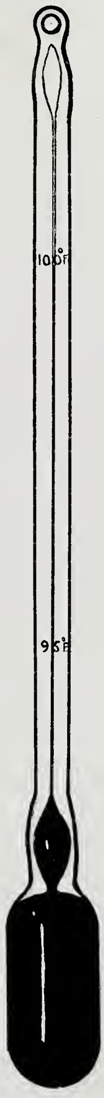

FIG. 1.

at the top of the stem and thus formed an unbroken column. The bulb is then withdrawn and wiped dry. The time for the alcohol to recede from the 100° to the 95° mark is then taken in seconds, and the "kata-factors" marked on the stems of the instruments are divided by this time, giving the cooling power of the atmosphere in millicalories per square centimetre per second.

The formula used for the kata-thermometer when testing it as an anemometer is of the form $V = \frac{1}{K}\left(\frac{H}{\Theta} - d\right)^2$

where V = velocity of the air in miles per hour

H = loss of heat of the instrument in millicalories per square centimetre per second.

Θ = $(36.5^{\circ} - t^{\circ})$ centigrade t being the temperature of the surrounding air.

d and k are constants for the instruments.

This formula was deduced theoretically by Hill, Griffith and Flack[1] and can also be obtained from King's analysis[2] for his hot wire anemometer.

There is some difficulty in getting correct values for K and d for a given instrument, but in practice a calibrating factor is obtained by comparison of the rate of cooling of new instruments with standard instruments under similar conditions.

Rearranging the above formula we have

$$H = (d + K\sqrt{V})\,\Theta$$

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1. Loc. cit
2. L.V.King. "The linear hot-wire anemometer and its applications in technical physics." Jour. Frank. Inst. Jan., 1916, pp. 1-25 where a complete list of references is given.

where it can be seen that $d\theta$ is the loss of heat due to radiation and "natural convection" which by chance[1] when the two effects are combined, is a linear function over ordinary ranges of temperature. The other term $K\sqrt{V}\theta$ is that due to movement of the air other than natural convection.

The original work of Hill gave d = 0.27 and K = 0.36, but the latest value for K as given by the makers of the kata-thermometers[2] is 0.47, and this value has been used in this paper. To find the rate of heat loss from the bulb per square centimetre per second a simple formula is used which is as follows:

$H = \frac{F}{T}$ Where F is a calibration factor determined by the maker and marked on each instrument, and which depends on the heat capacity of the bulb and its contents, and upon the emissivity of the surface.

T is the time in seconds for the temperature of the bulb to fall from 100°F. to 95°F. as indicated on the stem.

During the course of the experiments to be described it became necessary to make a new kata thermometer so that it could be sealed to the inside of a vacuum flask. The procedure taken and the data obtained for this piece of work will serve to shew how the instrument is calibrated and how the kata-factor is obtained.

The bulb was blown separately and later sealed on to a long capillary tube. The two indicators of temperature 95°F. and 100°F.

1.

2. Jas. J.Hicks, 8,9,and 10,Hatton Garden, London, E.C.

respectively were etched on the stem by comparison with a standard mercury thermometer reading to $\frac{1}{100}$ th. of a degree F. The kata-factor which is discussed elsewhere in this paper is a number which, when divided by the time of cooling in seconds, will give the number of millicalories heat loss per sq-cm. per sec. It was found by direct measurements and the result checked by comparison with another kata under standard conditions as described below.

In the construction of the new kata-thermometer the following data was obtained:

The weight of the completed thermometer with alcohol, and string for suspension on the scales	= 26.570	grams.
Weight of the glass	= 20.391	"
" " " string	= 0.179	"
" " " alcohol inserted therefore is	= 6.000	"
The specific heat of alcohol was taken to be	= 0.548	
and the water equivalent of the alcohol	= 3.528	"
The weight of the glass bulb alone was	= 4.955	"
and with a specific heat of 0.117 its water equivalent	= 0.579	"
The total water equivalent of the glass bulb, and contents was therefore	= 4.107	"

The surface of the bulb was divided for calculation into three parts, i.e. the cylindrical middle part, the semi-spherical lower end, and the partially semi-spherical upper end, which is sealed to the stem.

The cylindrical surface area $= \pi \times 1.9 \times 2.6 = 15.4\ cm^2$

where diameter $= 1.9$ cms. and length $= 15.4\ cm^2$

and lower end area $= 4\pi r^2 = 5.02\ cm^2$

the upper end " $= 4\pi r^2 - .8 = 4.22\ cm^2$

Total surface area of bulb $= 24.64\ cm^2$

Heat loss in calories cooling 100 to 95°F.

$= 4.107 \times 5 \times \frac{5}{9} = 11.4$ calories

$= 11.400$ millicalories.

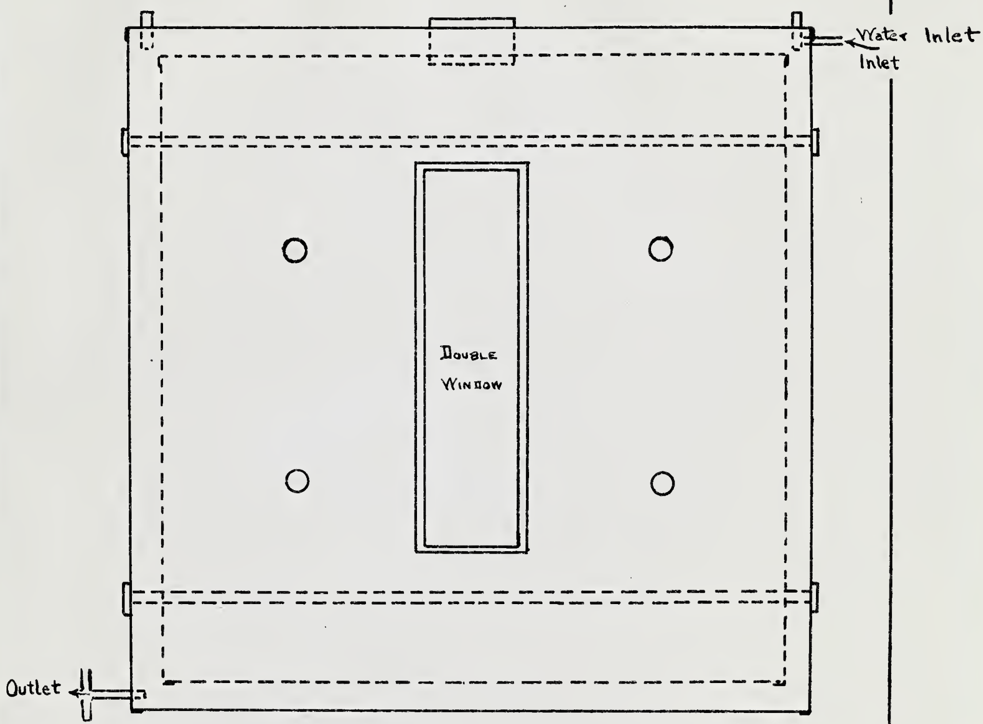
For 24.64 sq. cms. of surface the loss of heat per sq. cm. in cooling $5°F. = \frac{11.400}{24.64} = 463$ approx. $= F.$

Dividing this number by the time of cooling will give the heat loss in millicalories per sq. cm. per sec.

For a cylinder of similar shape the designers of the kata-thermometer have given the formula $H = 0.27\theta$ where H = heat loss per sq. cm. per sec. θ = difference between the average temp. of the bulb and the surrounding air.

Under conditions where the surroundings are at the air temperature, and the air is stagnant, H may also be determined by the formula $H = \frac{F}{T}$ if the kata factor be known and the time of cooling be observed.

The new kata was accordingly hung in a large double-walled cube which was kept at constant temperature by circulation of water between the inner and outer walls. (see Fig.3). The readings of the kata could be taken through a double window. The average time of cooling of a number of readings was 107.0 seconds



ELEVATION

DOUBLE WALLED CUBE

FIG. 3.

$\theta = 16.5^{\circ}C$. Equating 0.27θ to $\frac{F}{T}$ we have $F = 0.27\theta T$. We are thus able to obtain a separate value for F which on substituting for θ and T gave 476.

The discrepancy between this and the other value 463 is to be expected since the constant 0.27 may not strictly apply to this instrument, and on the other hand the area of the bulb and its weight could not be determined with precision. The second of these two values of F was used in obtaining results, since it was considered the more accurate.

In later publications by the makers of the kata-thermometers the constant 0.27 has been reduced to 0.20 for stagnant air, but the experiments described here would seem to indicate that 0.27 was nearer the correct value.

As mentioned before, in using the kata-thermometer in the open air considerable irregular variations in the readings were noted and could be explained by assuming that these were in part due to the irregular distribution of the incident radiation from surroundings. Since the incident radiations could not be screened off without altering the air currents under investigation at the time, efforts were made to make allowance for this by experimental means. The rate of cooling of the warm bulb of a dry kata- thermometer depends upon (1) the temperature of the air, (2) the movement of the air around it, and (3) the radiation to and from surroundings. Since the last two factors varied simultaneously sometimes combining and sometimes opposing in their influence on the readings of the instrument, the problem to be solved therefore,

was the measurement of the relative magnitudes of these two factors during any interval of time. The solution of the problem in this particular case at once revealed a means for approximately determining these same factors which are involved in the problems mentioned in the introductory paragraphs.

CALIBRATION OF A KATA-THERMOMETER FOR THIS WORK, AND PREPARATION OF THE SPECIAL CHARTS.

3 (a) The heat loss of the ordinary kata-thermometer when in very high vacuo and surrounded by walls at known temperature.

The results of previous tests[1] indicated that the glass bulb containing the coloured alcohol had very nearly the same emission and absorption powers as when the bulb had been covered with a thin coating of dull black paint. Since it is impossible to obtain a high order vacuum with anything but the cleanest glass surfaces, this was an important fact. The top of the stem of the ordinary kata-thermometer was such that it could not be sealed on to another glass surface, so a new one having a specially long stem was made and calibrated as described in Section 2. A two-litre round bottomed flask was selected as suitable for a containing vessel and the new kata-thermometer was sealed into the top of the flask, the neck of which had been drawn and closed. See Fig. (2). The kata bulb was put at the centre of the flask and two additional tubes were sealed into the top, one leading into a

1. Two identical katas were used with the same factor for each. One was dipped in a solution of lamp black in amyl acetate, withdrawn and allowed to dry. A very thin, smooth, dull, black coating resulted. Each thermometer was subjected to the same conditions of radiant heat and convection currents and allowed to cool. The general conclusion from the results was that the surfaces were practically equivalent and that, with the ordinary kata, it is a case of black body radiation.

Fig. 2.

large charcoal bulb and the other to a specially constructed and very sensitive McLeod gauge, and a mercury diffusion pump. The apparatus was arranged in such a manner that the flask could be completely submerged in large vessels of water serving as a temperature bath. In operation it was first immersed in boiling water until the alcohol within had risen to the top of the thermometer. The hot water was rapidly withdrawn and water at approximately the required temperature substituted until the thin-walled flask was at that temperature. There is plenty of time for this when the vaccuum is high. The large vessel of water was again replaced by one containing water at a known temperature which could be kept constant to within 0.02°C. The time during which the alcohol was passing down the graduated stem of the kata was comparatively long and there was ample time for the preliminary operations to be completed, and to allow the glass flask to come to its final temperature before the first record had to be taken. These operations were done repeatedly while the pressure was being gradually reduced by the mercury pumps, and readings at different known pressures were obtained as follows:

For the sake of clearness this table is shown on the next page.

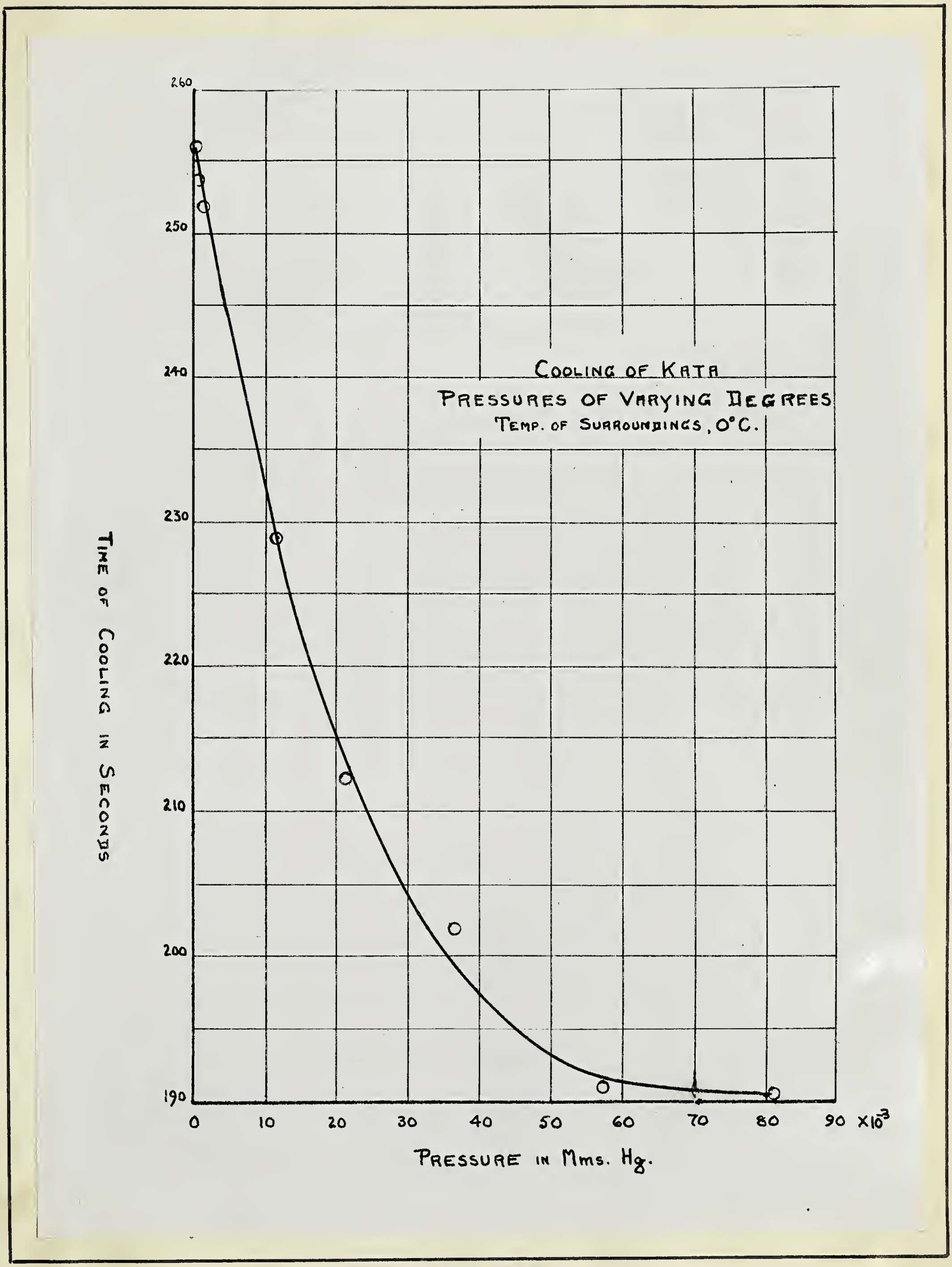
Average temperature of Kata bulb = 36.0°C.

Averages of times of cooling	Temperature of Outer bulb	Pressure on McLeod Gauge
191.0 secs	19.00°C.	.0811 mm.Hg.
192.0 "	19.00°C.	.0570 " "
202.0 "	19.00°C.	.0385 " "
213.5 "	19.00°C.	.0217 " "
227.3 "	19.00°C.	.0106 " "
253.8 "	19.00°C.	.00003? "
256.4 "	19.00°C.	.00001? "
258.8 "	19.00°C.	Five hours with liquid air applied to charcoal bulb. Pressure unreadable.

When the gauge recorded only 10^{-5} mms. hg. a ground glass mercury sealed tap was turned and the apparatus cut off from the pump. The charcoal tube was next submerged in liquid air for about five hours and the above operations repeated. Only slight differences were noted in the times of cooling of the liquid under these conditions and at a pressure of 10^{-5} mms. The slope of the curve (Fig.4.) where these values are plotted supports this result. The conclusion therefore is that the transfer of heat was almost entire -ly by radiation.

(b) Calibration of the Silvered Kata-thermometer

For this experiment and also to enable the newly made kata-thermometer to be calibrated, a large double-walled cube of galvanized iron was made about 30 inches inner dimensions. See Fig.(3) The surrounding cavity had a capacity of about 50 gallons, and the



Cooling of Kata
Pressures of Varying Degrees
Temp. of Surroundings, 0°C.
Time of Cooling in Seconds
Pressure in Mms. Hg.
260
250
240
230
220
210
200
190
0
10
20
30
40
50
60
70
80
90 X10-3

Fig. 4.

whole was enclosed in a large box and insulated on all faces by dry sawdust and layers of paper. The cube had a hole cut at the top which allowed access for the katas to the interior, which was painted black. Two narrow plate glass windows, one in each of the inner and outer walls, allowed a clear view of the kata inside when illuminated by diffused light from behind the observer. Water from a heater was allowed to enter from the top and flow out from the bottom over a trap so that after a certain time interval the temperature of the walls of the cube and the air within could be brought to and kept accurately at any given temperature. When ice water was used from a reservoir it was allowed in at the bottom. The silvered kata was heated in an oven at a moderate temperature (immersion in hot water spoils the polish) and inserted through a felt cover over the hole, and its time of cooling observed. This was repeated a number of times for each temperature, and for various temperatures of the walls. The insignificant amount of heat from the cooling kata had no measurable effect on the temperatures of the air within, and the water between the windows intercepted entrance of any radiation of heat from without. The conditions inside were therefore the standard conditions desired.

The silver on the silvered kata-thermometer was found to be a quite negligible amount in so far as it might alter the heat equivalent. The reflecting power of polished silver for light waves is usually given as about 90%, and for heat waves at ordinary temperature its reflecting power should be increased. The error in assuming that the silvered surface is a perfect reflector, and

a corresponding nil emitter will not be large.

Placing the silvered thermometer, therefore, inside the constant temperature cube described above, it will cool almost entirely by means of convection currents set up by its own excess of temperature. Radiation will have very little to do with it, Having obtained a set of values for the cooling at various temperatures in this manner, the heat loss in millicalories per sq. cm. per sec. for each difference of temperature was calculated by making use of the kata factor, and the relation $H = \frac{F}{T}$ where symbols have meaning assigned earlier in this discussion.

(Note) - See next page for Table of Observations.

Silvered Kata in Water Jacketed Cube

$F = 522$

Temp. °C.		Time of Cooling in Seconds (T)	Θ	$H = \frac{F}{T}$
25.6		301.0	10.9	1.7
		301.0		
		301.0		
	Mean	301.0		
19.3		169.0		
		169.0		3.0
		169.0		
	Mean	169.0	17.2	
17.0		144.0		
		144.0		3.6
		144.0		
	Mean	144.0	19.5	
15.8		130.4		
		130.2		3.98
		130.2		
	Mean	130.3	20.7	
12.9		116.6		
		120.0		4.4
		118.0		
	Mean	118.2	23.6	
8.0		91.8		
		93.0		5.6
		92.4		
	Mean	92.4	28.5	
4.8		83.6		6.2
		84.4		
	Mean	84.0	31.7	

When these values of H were plotted against Θ, the points were found to lie almost exactly on the curve which would be drawn if the ordinates of the curve for the kata in vacuo cooling by radiation only were subtracted from the ordinates of the theoretical curve $H = 0.27\ \Theta$. The equation of this curve for the silvered kata need not be worked out since its representation by a graph is sufficient for the purposes desired.

(c) Preparation and description of Chart (Fig.5)

All the curves in this chart are plotted on the absolute basis of millicalories per square centimetre per second (H) against the difference (Θ) in temperature between the mean temperature of the bulb and the air temperature. This means that, within reasonable limits, it does not matter what kata-thermometer is used provided the correct kata-factor is known. When this factor is divided by the time of cooling in seconds it gives (H) in mcs./cm^2/sec.

Curve No.II was obtained from data by the method shown in subsection (a) of this section. It gives (H) lost by radiation only. Owing to the difficulty of technique in this part of the experiment, and of obtaining sufficient liquid air, only three points were obtained but they were the result of a number of observations as tabulated on the following page.

	Time of Cooling	Temp. of surroundings	$(\bar{3}6-t)$	H in mcs./cm.^{2}/sec.	Remarks
	137.2 secs.	0.0°C.			Liquid air,
	138.2 "	"			applied to
	136.8 "	"			charcoal bulb
	137.6 "	"			for nine hours,
	136.4 "	"			kept pressure,
	138.4 "	"			originally reduced
Mean	137.2		36.0	3.56	by mercury pump
	179.0	10.0°C			below .00006 mms.,
	176.8	"			less than a
	178.6	"			readable amount.
	179.8	"			See Subsection (a)
	177.4	"			
Mean	178.2		26.0	2.67	
	258.8	19.0°C.			
	256.8	"			
	256.2	"			
	257.0	"			
	260.0	"			
Mean	257.5		17.0	1.85	

Curve No.I is plotted from the values shown in part (b) of this section and are for the heat loss of the silvered thermometer in still air. This curve shows what the loss of heat would be from an ordinary kata if all radiation effects could be eliminated.

Curve H = 0.27 is the theoretical curve for the instrument as mentioned in section (2) where there are no extra air movements, and standard conditions of radiation. Curve No. III is the resultant curve of the Curves I and II.

The curve which might be drawn through the points enclosed with circles would be that for the experimental results of the ordinary kata cooling in the double walled cube under standard conditions. It is therefore evident that these experimental results are consistent within themselves, but that the constant (0.27) should be slightly larger under still air conditions. There is also some evidence that the law applying is not strictly linear.

THE METHOD

Sect.4 The method makes use of simple apparatus consisting of two kata-thermometers and a stop watch. One of the kata-thermometers had its bulb and lower stem carefully silvered and polished. Kata-thermometers are very suitable because they may be arranged to give simultaneous records of their own loss of heat. To determine the respective quantities of heat transferred by convection and radiation to or from a dry body[1] which differs in temperature from its surroundings, the following procedure is carried out:

1. If the body is moist a further observation must be added to the set as given. A wet-bulb kata having appropriate sack and known calibration factor must be used. The cooling due to evaporation can then be sorted out from that due to other causes as in the ordinary use of the wet kata.

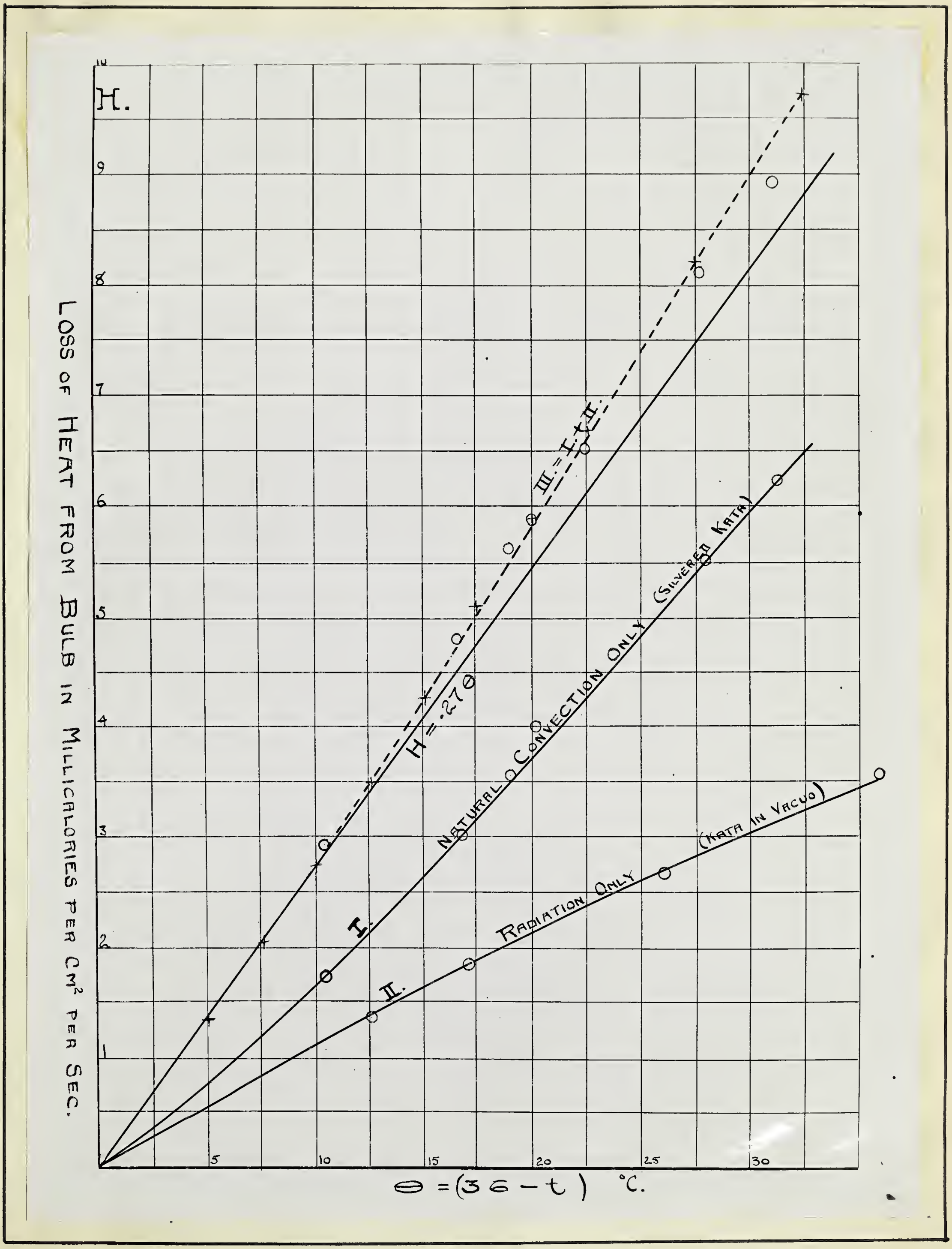

H.
Loss of Heat from Bulb in Millicalories per Cm² per Sec.
III. = I. + II.
H = .27θ
I.
Natural Convection Only (Silvered Kata)
II.
Radiation Only (Kata in Vacuo)
1
2
3
4
5
6
7
8
9
5
10
15
20
25
30
θ = (36 − t) °C.

FIG. 5.

1. A reading of the rate of cooling of the unsilvered kata-thermometer is taken at the place where information is desired.[2]
2. A reading of the rate of cooling of the silvered kata-thermometer is taken either concurrently or immediately afterward.
3. The temperature of the air is obtained from a screened thermometer.
4. Two values are read from charts (vide opposite page) which show (a) the rate of loss of heat by the ordinary kata-thermometer in stagnant air and all surroundings at air temperature and (b) the rate of loss of heat by the kata-thermometer by radiation only, in extreme vacuo, both charts covering the possible differences in temperature between the kata-thermometer bulb and the surroundings. These charts were obtained by special calibrations in the laboratory which are described in Sect. 6, but they can be made to serve for any ordinary kata-thermometer.

When the air movement is sluggish, readings for number (1) show the loss of heat due to three causes, namely, cooling by convection currents set up by the kata-thermometer itself (hereafter called "natural convection"), cooling by other movements of the air, and cooling by radiation if the surroundings are at a lower temperature than the bulb of the kata-thermometer.

Readings for number (2) indicate approximately the rate of cooling due to the first two influences mentioned above; i.e. natural convection and other air movements.

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2. If the emissivity of the surface of the cooling body is not of the same order as that of the kata-thermometer, the unsilvered kata-thermometer should be covered with a thin coat of paint (or a close contact jacket) of the same kind as on the surface of the cooling body under investigation. If this is necessary, the calibration factor of the instrument must, of course, be determined in this new condition.

Readings for number (3) will give the difference between the temperatures of the bulb and the air for use in referring to the chart.

Although the readings for the cooling of the kata-thermometers are taken in seconds and indicate the time of cooling of the bulb from 100°F. to 95°F., they can be readily converted to show the loss of heat from the bulb in millicalories per square centimetre per second by dividing the time of cooling into the calibration factor for the particular instrument as in its ordinary use. This has already been explained in Sect. 2. It will be clear that for special purposes the range 100°F. - 95°F. required for comfort gauging measurements will not necessarily be the most sensitive for much of this work. In this article the possibilities of the method are discussed in terms of the standard form of kata, because it was the only type available, and it is obvious if the tests can be made satisfactorily with this instrument that the development of the method with types specially designed for the work can follow readily. Sensitive self-recording instruments with variable cooling ranges, or arranged for maintenance at constant temperature by recorded and self-regulated electrical heating will be most suitable for work requiring higher precision.

TESTING THE METHOD

ect.5 In order to test the method a series of experiments was made in the laboratory where there were no stray air currents, and where fairly constant conditions of temperature and radiation could be obtained. The following simple test constitutes a certain demonstration of the soundness of the method. If a beam of thermal radiation and a strong air current were made to pass

simultaneously through a certain space where the kata readings could be taken, then a striking test of the method would be to perform the necessary procedure and predict what the readings would be if either the air current or the thermal radiation or both were turned off. These predicted readings could at once be verified.

The apparatus consisted of an electric heater, or a bank of heating lamps, an electric fan of variable speeds, a screened thermometer, an ordinary kata-thermometer, a stop-watch, and a supply of hot water, or a heated solid copper beaker over a flame.

The kata-thermometers were hung so that air currents arrived at the instruments without being heated in any way by the heaters which were arranged to give incident radiation at right angles to the stream of air. (PLATE I.) For obvious reasons a large closed inner room was selected where the walls would be very approximately at air temperature.

The first part of the procedure was to take several observations with the silvered thermometer. As previous calibtrations had shown, the slight absorption of incident radiation, and the radiation from within, on the part of the silvered surface could be neglected. The average of these observations gave the heat loss due to air movement. Certain experiments were made with a kata-thermometer, enclosed in a narrow tube and partially exhausted, where the outer glass was alternately at bulb temperature and at air temperature to begin with, and exposed to variable air currents. These indicated that above a velocity of three miles per hour

PLATE 1.

"natural convection" is merged into the moving stream of air, and its independent effect on the cooling is relatively negligible, and indeed reduced in magnitude.

Several observations were then taken with the ordinary kata-thermometer hanging in the same position. The heat loss in this case was affected by the incident beam of radiation.

By means of the permanent calibration graph (Vide Fig.5 .) showing heat loss by radiation only to surroundings at various temperatures as determined by experiments described in section three, the amount of heat may be read which the silvered kata would have lost to surroundings at air temperature by radiation if the silvering had been removed.

Now the unsilvered kata radiates this amount of heat, but it receives more on account of the heating lamps. Therefore, when we add the amount obtained from the calibration graph, to the loss of heat from the silvered kata, and take the difference between this and the reading of the ordinary kata, we obtain the amount of heat being absorbed in excess of that received from the surroundings at air temperature. Also it may be seen that if this amount were added to the reading of the ordinary kata it should have given the heat loss when the lamps were turned off. Turning off the lamps therefore, the result of several readings serve as a check on the method. The results of one experiment are shown on the following page.

Kind of Kata-thermometer	Time of Cooling	Heating Lamps	Fan	Temp. of Air	Heat Loss
A ordinary	43.2	on	on	21.7°	in Millicalories per cm^2 /sec.
"	43.0	"	"	21.7	
"	43.6	"	"	21.7	
"	43.6	"	"	21.7	
	43.1				Mean 10.9
B silvered	35.8	"	"	21.8	
"	35.4	"	"	21.8	
"	35.6	"	"	21.8	
	35.6				Mean 12.4
C ordinary	33.6	off	"	21.8	
"	34.6	"	"	21.8	
"	34.6	"	"	21.8	
"	34.6	"	"	21.8	
	34.1				Mean 13.8

D The value of heat loss by radiation from the chart (θ = 36-21.8) is 1.3 mc./cm^2/sec.

From the above we see that the silvered thermometer cools more quickly than the other in the beam of heat rays. The reverse is true under normal conditions when all surroundings are at air temperature. Adding the chart reading (1.3) to the silvered kata heat loss we can predict the figure 13.7 which compares with 13.8 when the heat is turned off. (It must be remembered that the wind velocities were considerable, say from 6 to 10 miles per hour.) Also subtracting the ordinary kata heat loss from 13.7 we get 2.8 which is the heat gained in excess

from the heating lamps and 2.8 + 10.9 = 13.7 which was the predicted value for (C). When the incident rays are feeble, this illustration in itself demonstrates the sensitivity of the method in a striking manner.

A second experiment was conducted replacing the heater by a fairly large tin box, filled with small ice, whose outer surface was painted black. The fan was allowed to throw a stream of air past the kata-thermometers as before so that no cooled air could affect them, and the katas were placed near enough to have the radiation conditions affected by the cool surface. When the cold surface was to be brought up to normal or room temperature, a sheet of heavy black cardboard was slipped over the front of the surface without touching it. This allowed the wind conditions to remain the same. Throughout these experiments the room temperature was kept constant.

A typical set of observations is shown on the following page.

Kind of kata-thermometer	Time of Cooling	Ice Box	Fan	Temp.	Heat Loss in Millicalories /cm.² / sec.
A ordinary	41.4	Surface Exposed	on	21.0°	
"	43.6	"	"	21.0°	
"	43.0	"	"	21.0°	
"	42.8	"	"	21.0°	
	42.6				Mean 11.0
B silvered	47.4	"	"	21.0°	
"	48.6	"	"	21.0°	
"	49.0	"	"	21.0°	
"	48.2	"	"	21.0°	
	48.3				Mean 9.1
C ordinary	45.3	Covered	"	21.0°	
"	44.2	"	"	21.0°	
"	44.0	"	"	21.0°	
"	44.5	"	"	21.0°	
	44.5				Mean 10.6

D The Chart (see Fig.5, Curve No.II.) shows that the heat loss by radiation only at 21.0°C is 1.5. Therefore the total amount of heat which the silvered kata would lose if unsilvered in normal surroundings would be 9.1 + 1.5 = 10.6 millicalories per cm.² / sec. This checks closely with the experimental result as before. Further the heat loss of the unsilvered thermometer with ice cooled surface exposed is 11.0 and 11 - (9.1 + 1.5) = 0.4 mcs./cm.²/sec., which is the additional heat lost to the cold surface because of its subnormal temperature.

The experiments described above are two of a number which

have been performed with variable amounts of incident radiation and air currents giving similar good agreement provided the conditions of temperature and electric current supply could be kept constant.

Recapitulating some of the previous discussion we note that the readings of the silvered thermometer give air motion effects only. The readings of the unsilvered thermometer give loss by air motion plus the algebraic resultant of exchange of radiation. If the surroundings are at the temperature of the air, "standard" exchange of radiation is obtainable by reference to the chart. But if the temperature of the surroundings is not known and the loss of the silvered kata is greater than the ordinary one, then we know that on the average the surroundings are higher in temper- than the air and higher than the temperature of the bulb itself. Under "standard" conditions the silvered thermometer losses less heat than the ordinary unsilvered one by amounts as given by the chart. Therefore if they both lost heat at the same rate it would mean that the surroundings were at a sufficiently high temperature to contribute as much heat to the ordinary thermometer as it lost by radiation. That is, the equivalent temperature of the surroundings was the same as that of the average temperature of the bulb during the test. Again, if the silvered thermometer lost heat less quickly than the unsilvered one by an amount which from reference to the chart is that for standard conditions, then the equivalent temperature of the surroundings is less than air temperature.

Another experiment was performed, indentical in arrangements,

The procedure was to take readings with the ordinary and silvered kata in a stream of rapidly moving air and a beam of radiant heat as before, but then to turn off the fan and predict the reading of the ordinary kata. A good check can hardly be expected under these conditions, and has not been realized for the following reasons. The room becomes warmer in the vicinity unless ventilated and this usually would cause draughts. The walls rapidly heat up, as the readings under (C) shew, unless there is moving air to keep them cool. A large room would likely have walls at irregular temperatures and be draughty. This is why an inner room with thick walls and no windows has been used for all experiments. The surface of the bulb exposed to the strong incident beam would be warmer than the other side, and "natural convection" would be less than under normal circumstances. The stem of the thermometer also becomes appreciably warmer and the descending column of liquid feeds into the bulb at a higher temperature than under ordinary conditions. The observations and results of a typical experiment are given rather for the sake of completeness than for the good approximation which the prediction attains to the actual results.

Test with Ordinary and Silvered Katas in the Presence of fan and radiant heater to predict Reading of Ordinary Kata when fan is turned off.

	Ordinary Kata	Silvered Kata	Millicalories per/cm^2/sec.	Fan	Heater	Temp. of air	Remarks
A	38.8 secs.			on	on	19.4°C.	
	40.6			"	"	19.7	Supply
	40.0			"	"	19.6	voltage
	39.6			"	"	19.8	varying
	39.8			"	"	19.8	slightly
	39.6			"	"	19.6	
	39.6 Mean		11.85				
B		39.6 secs.		"	"	19.6	
		39.4		"	"	19.7	
		39.0		"	"	19.7	
		39.2		"	"	19.7	
		39.0		"	"	19.8	
		Mean 39.2	12.00				
C	110.4		4.27	off	"	19.6	Temperature was
	116.8			"	"	19.7	lowered by
#	124.4			"	"	19.8	opening a door
#	128.6			"	"	20.0	slightly
#	129.2			"	"	20.0	
#	132.0			"	"	19.6	

These readings indicate the fact that the longer the heat is on without a fan, surrounding surfaces become increasingly warmer. When the ordinary kata was used immediately after with the fan and heater on, it cooled in 43.0 secs. which indicates

that incident radiation has increased from surroundings.

Analyzing the results of this experiment, we note that the ordinary kata in the presence of a rapid stream of air, at 19.7°C. and incident radiation loses 11.85 mcs./cm.^{2}/sec. Also that the silvered kata under the same conditions loses 12.00 mcs./cm.^{2}/sec. It must be kept in mind that the incident radiant heat comes from a relatively small area and that the walls and surfaces of the room are at air temperature. If the silvering were removed from the second kata then for a difference in temperature of 25.3°C. = θ and referring to chart (Fig.5) 2.75 mcs./cm.^{2}/sec. additional would be lost. A slightly more than equal amount of heat by incident radiation from the heater is apparently gained however, and this accounts for the two readings being nearly the same. The 12.00 mcs./cm.^{2}/sec. lost by the silvered kata is due to air movement only.

When the fan is turned off however, this loss is cancelled out, but is replaced by a heat loss due to "natural convection" of 5.0 mcs/cm^2/sec. which is read from(Curve I. Fig.5) when θ= 25.2°C. This value is probably higher than applies to the kata in still air and in the path of a strong beam of radiation.

The conditions of radiation for the ordinary kata apart from heating up of walls after a time are identical before and after the fan is turned off. Therefore applying the net result of heat loss cancelled by stopping the fan and supplied by"natural convection" to the reading"A" we should be able to predict the value under "C". i.e. 11.85 - 12.00 + 5.0 = 4.85 mcs./cm.^{2}/sec.

The actual result as shewn in C for the first reading is 4.27 mcs./cm.^{2}/sec. Considering that there was an interval of over two minutes unavoidably necessary for the taking of the reading and during which heating of surrounding objects and the stem was taking place, this is a fair agreement.

PRACTICAL APPLICATIONS

Sect. 6 In order to show how the method described in the foregoing pages may be applied in practice, the readings and implications of an experiment conducted in Convocation Hall of the University will be given. It was a windy cold day outside, and the temperature was rather high inside. All the steam radiators were in operation on both sides of the hall, but the upper windows, being very cold and directly overhead, caused draughts which were distinctly noticable to the face as was the sensation of radiant heat some fifteen feet out from the radiator line.

The silvered and the unsilvered katas were hung side by side some six inches apart and a set of readings was taken simultaneously by two observers with stop-watches as follows:

Time of Cooling 100°F. and 95°F.

rdinary Kata	Silvered Kata	Temp.	= (36-t)°C.
106.0 secs.	136.0 secs	22.2°C.	
106.0 "	140.0 "	22.2°C.	
108.0 "	144.4 "	22.2°C.	13.8
Mean 106.6	Mean 140.1		

$H = \frac{F}{T} = \frac{470}{106.6} = 4.4$ $H = \frac{F}{T} = \frac{440}{140.1} = 3.1$

Subtracting the heat loss per sq.cm. per sec. for the silvered kata from that of the ordinary kata we get (4.4 - 3.1)= 1.3 which is due to excess radiation of the bulb to surroundings. We note that by Curve II, chart 5, for θ = 13.8 that the heat loss for radiation only for surroundings at air temperature is 1.5 mcs./cm.^{2}/sec. The difference between this value and 1.3 indicates that 0.2 mcs./cm.^{2}/sec. is being received in excess of standard conditions. In other words a body at blood heat cools 13% less rapidly than if all surroundings were at air temperature.

Referring again to chart 5, Curve I, we see that in still air and at the temperature under consideration H = 2.4 mcs./cm.^{2}/sec. per sec. The difference is 0.7 and this means that draughts in excess of "natural convection" carried away this number of mcs./cm.^{2}/sec. from a body at blood heat. In other words cooling was increased by 18% above that in still air.

The general conditions resulting from both radiation and air

movement factors is a slight decrease in cooling over so called "standard conditions" and would be called comfortable.

The instruments were then removed to one end of the hall at considerable distances from the radiators and still in draughts, but the air temperature was approximately the same.

Another set of readings was taken simultaneously which are tabulated as follows:

Time of Cooling 100°F. to 95°F.

	Ordinary Kata	Silvered Kata	Temperature	= (36-t)°C
	62.8	87.6	72.0°C	
	66.6	80.3	22.2	
(1)	79.0	99.0	22.0	13.9
Mean	69.6	Mean 88.9		
	H = 6.75	H = 4.9		

Condensing the argument as given in the previous set of results, we see that excess cooling by radiation is (6.75 - 4.9)=1.85 mcs./cm.^{2}/sec.

By Chart 5, Curve II, as before, radiation only gives 1.5 mcs./cm.^{2}/ sec. the heat loss is greater than this by0.35 mcs./cm.^{2}/sec. That is to say a body at blood heat would cool 44% more rapidly by radiation than under "standard conditions." This indicates that the walls and windows are considerably below air temperature.

1. The fact that these readings are not constant is of course not to be expected since draughts were irregular, but both thermometers were affected together. If radiation varied rapidly the silvered kata-thermometer would not show it, however.

Again, cooling due to draughts is (4.9 - 2.4) = 2.5 mcs./cm.^{2}/sec. This means that cooling due to air movements is double that due to "natural convection" alone.

Altogether the results in the second location indicate general rapid cooling conditions for a warm body, and even though the air temperature was the same, conditions were distinctly uncomfortable.

Similar observations at different regularly spaced points throughout the room might have been taken showing where the radiation was in excess or below "standard conditions", and air movement likewise. This would constitute a kind of thermal survey and if the results were tabulated, would reveal information of value to the heating engineer and to anyone interested in the comfort of the individual in an auditorium.

Some work which remains to be done amongst applications mentioned in the introduction is (1) convection versus radiation when the sky is clear, or again when cloudy. (2) to compare the radiation with the convection above and below:- (a) a large-surface-black-insulation-covered wire carrying a heavy electric current, and (b) the same wire bare carrying the same current. This is already an important problem to electrical engineers since there are apparent paradoxes In this case losses could be checked by measurement of current in the wire. Other possible applications are mentioned in the introduction.

CONCLUSION

To summarize the work performed to date and explained in this thesis, a practical method of sorting out radiation from

"natural convection" and air movement has been described. The necessary experiments required to obtain the calibrations and to provide checks on the method have been included. An indication of how the method has been applied in one practical case is given in detail. Further investigations make it clear however, that for the particular purpose of investigating conditions where the air temperature is high and the air still, a new form of kata which would enable one to work over ranges of temperature other than 100°F to 95°F will ultimately be better.

The greater part of the work recorded above was done at the MacDonald Physics Building, McGill University, where every facility for the work was afforded which included the supplying of considerable quantities of liquid air.

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